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A tunable terahertz filter and its switching properties in terahertz region based on a defect mode of a metallic photonic crystal

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We theoretically investigate and discuss an electrically tunable terahertz filter design and its optical switching properties based on the defect mode of a woodpile metallic photonic crystal (MPC). The model filter design is based on a dual use of an MPC as a resonator and as electrodes with a liquid crystal used as a defect layer. The static and the dynamic responses of a realistic liquid crystal are obtained using the Oseen–Frank elastic continuum theory, and the corresponding transmission spectra are calculated using an analytic modal expansion method combined with a transfer-matrix method. The tuning range of $f = 1.430 \sim 1.577$ THz and the order of milliseconds switching property are observed in our design. © *2011 American Institute of Physics*. [doi:10.1063/1.3603009]

I. INTRODUCTION

Recently, terahertz (THz) technology has attracted a growing attention because its potential applications such as medical and security imaging, communication, etc. THz radiation uses low energy sources (less invasive), and it can pass through many non-metallic materials such as clothing, paper, plastic, and ceramics. These make THz imaging attractive in medical and security imaging areas.[1] Also, wireless short range THz communication systems are expected to be developed in near future due to the increased demand of communication bandwidth.[2] For high-resolution THz imaging applications, widely tunable high-efficient narrowband THz filters are necessary to improve image quality.[1] To develop a communication system operating at THz frequencies, it is necessary to develop THz optical components such as emitters, detectors, frequency filters, and switches working in the THz range.[2] Therefore for further advances in the above applications, widely tunable THz filters and switches are commonly required.

There have been several studies to develop tunable THz filters and switches. Nemec *et al*. have demonstrated the thermally tunable THz filters using defect modes in a one-dimensional photonic crystal.[3] Rivas *et al*. have demonstrated the thermal switching of THz transmission through a subwavelength two-dimensional (2 D) hole array.[4] Drysdale *et al*. have reported a continuously tunable THz filter using three-dimensional metallic photonic crystals (MPC) with mechanical shifting of two MPC plates.[5] Pan *et al*. have demonstrated a tuning property of THz transmission using the magnetic birefringence of liquid crystal.[6,7] Zhang *et al*. have also reported the theoretical design of THz switch and filter using the magnetic birefringence of 2 D liquid-crystal-filled photonic crystal.[8] In addition, Taylor and Chen have demonstrated ultrafast switching in THz regime using metamaterials.[9]

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In this paper, we propose a THz filter using the defect modes of a three-dimensional metallic woodpile photonic crystal. For the defect layer, realistic physical parameters of a commercially available liquid crystal, MLC-2048 (Merck), is considered.

II. DEFECT MODES OF A METALLIC PHOTONIC CRYSTAL WITH LIQUID CRYSTALS

Photonic crystals are three-dimensional periodic structures that can produce a photonic bandgap where the propagation of electro-magnetic (EM) waves can be forbidden for a certain range of frequencies. Especially, a three-dimensional metallic photonic crystal (MPC) has a wider photonic bandgap than its dielectric counterparts due to a greatly enhanced contrast in the dielectric constant of the composite materials.[10] By introducing an appropriate defect layer into a photonic crystal, a mode can exist in the photonic bandgap. This mode is called a defect mode and widely studied for potential applications such as lasers, resonators, etc.[11–16] The frequency of the defect mode can be tuned by changing the thickness or the refractive index of the defect layer.

A liquid crystal (LC) has two principal refractive indices, ordinary refractive index n_o and extraordinary refractive index n_e. The ordinary index is measured for the EM wave where the electric vector vibrates perpendicular to the optical axis. The extraordinary index is measured for the EM wave where the electric vector vibrates parallel to the optical axis. An appropriately treated surface can make LC molecules align in a specific direction near the surface, and the alignment of molecules at the surface propagates over macroscopic distances. An applied bias voltage can change the average alignment direction of the LC molecules (director n) as shown in the inset of Fig. 4. This can eventually change the effective refractive index of the whole LC layer. Thus the frequency of the defect mode can be tuned by applying bias voltage.

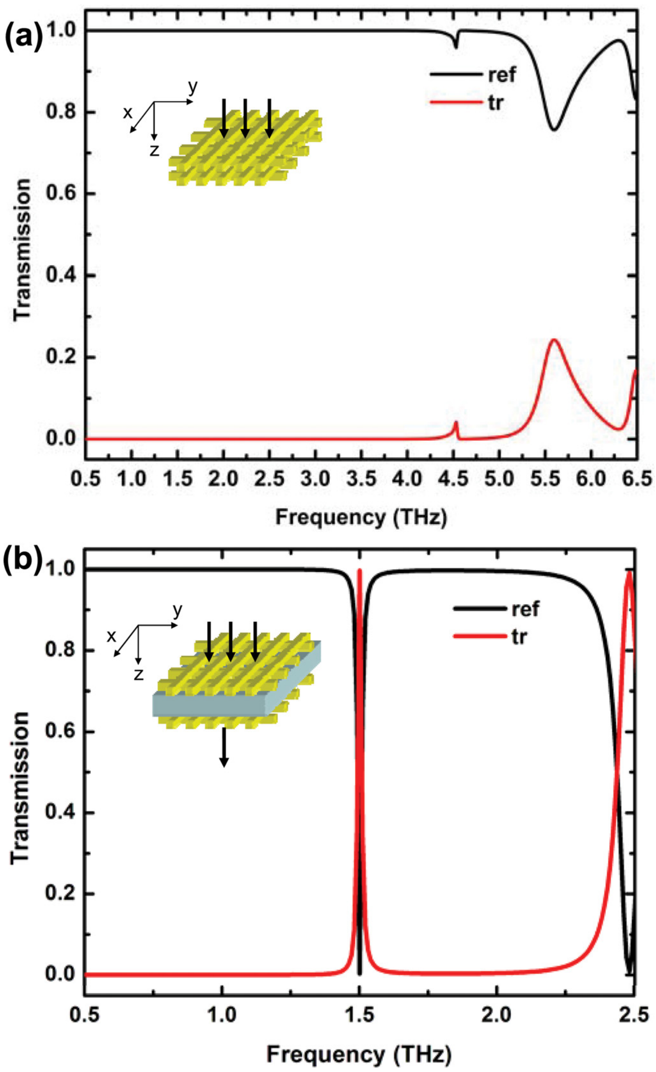

FIG. 1. (Color online) (a) Calculated spectra of the defectless metallic photonic crystal. (b) A defect mode due to the defect layer between the second and the third layer of the metallic photonic crystal.

III. DESIGN FOR THz FILTERS AND EFFECTIVE INDEX OF A LIQUID CRYSTAL

In Fig. 1(b) a schematic model of a woodpile MPC with a defect layer and the calculated optical spectra are presented. In the calculation, an analytic modal expansion method combined with a transfer-matrix method[17] and a perfect conductor approximation is used.[18] The MPC is consists of four layers of metallic gratings that are stacked with 90 degree rotation and a half of rod-to-rod spacing shift. The rod-width, $w = 30$ μm, the rod-to-rod spacing, $a = 65$ μm, and the thickness, $h = 5$ μm, are designed to yield a photonic bandgap in the range of 0.5 THz $< f <$ 3.0 THz (see Fig. 1(a)) along the z-direction that is perpendicular to each metallic layer. The space between the metallic rods in each layer is assumed to be filled with a low-loss dielectric material such as high density polyethylene ($n \sim 1.54$, $k \sim 0.003$)[19] to confine the liquid crystal defect layer inside the MPC. A liquid crystal defect layer is introduced between the second and the third layers. In the calculation, the refractive index of the defect layer is $n = 1.675$ and $k = 0$ and the thickness is 50 μm. The thickness is determined by considering a resonance condition representing a standing wave in the defect layer. The cavity length, the thickness of the defect layer, is approximately $l \sim c/(2nf)$, where c is the speed of light, n is the refractive index of the defect layer, and f is the frequency of an incident EM wave.

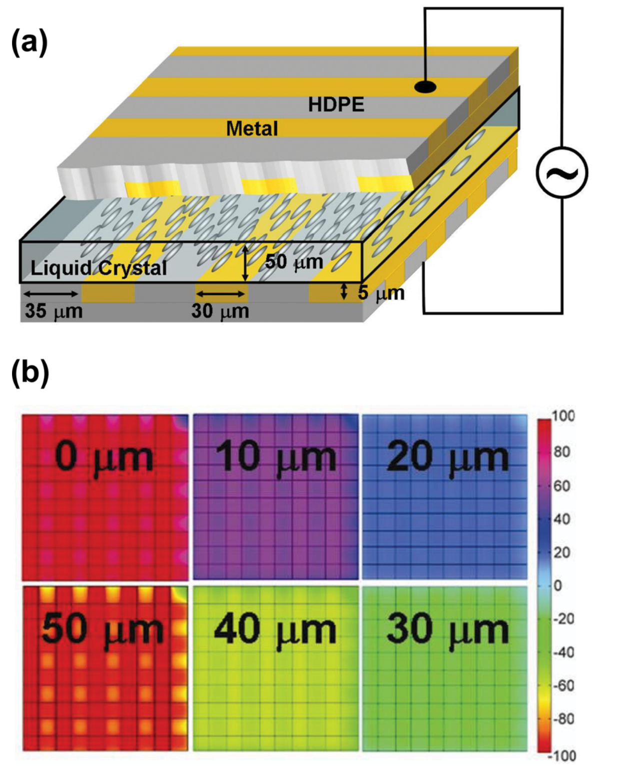

FIG. 2. (Color online) (a) A schematic drawing of the tunable THz filter. The liquid crystal is embedded between the second and the third layers of the metallic photonic crystal. (b) The distribution of electric potential as a function of spatial coordinate (x, y) at different depth $z = 0 \sim 50$ μm across LC layer from an electrode surface. The electric potential is almost uniform throughout the surface laterally that has the same depth (z) from an electrode.

The MPC in the design also serve as electrodes to apply bias voltage to the LC layer as depicted in Fig. 2(a). To control the refractive index of the LC layer appropriately, it is necessary for the MPC layers to generate a laterally uniform electric potential distribution at a certain depth in the LC defect layer. To see the uniformity of the potential distribution, the electric potential is calculated using a commercial software, COMSOL MULTIPHYSICS, based on the finite element method. For this calculation, 5×5-unit-cell-size domain and electrostatics mode are used. The calculated lateral distribution of electric potential is nearly uniform at a fixed depth throughout the LC layer as shown in Fig. 2(b).

With these calculated electric potential distribution and the parameters of an LC, the averaged effective refractive index of the liquid crystal layer, $\bar{n}_{eff}$, can be calculated. Based on the Oseen–Frank elastic continuum theory, the total free energy density g is given by

$$g = (K_{11}\cos^2\varphi + K_{33}\sin^2\varphi)\left(\frac{d\varphi}{dz}\right)^2 + \frac{D^2}{\varepsilon_1\sin^2\varphi + \varepsilon_2\cos^2\varphi}, \quad (1)$$

where K_{11} and K_{33} are the Frank elastic constants of LC molecules, ε_1 and ε_2 are the dielectric constants that are parallel

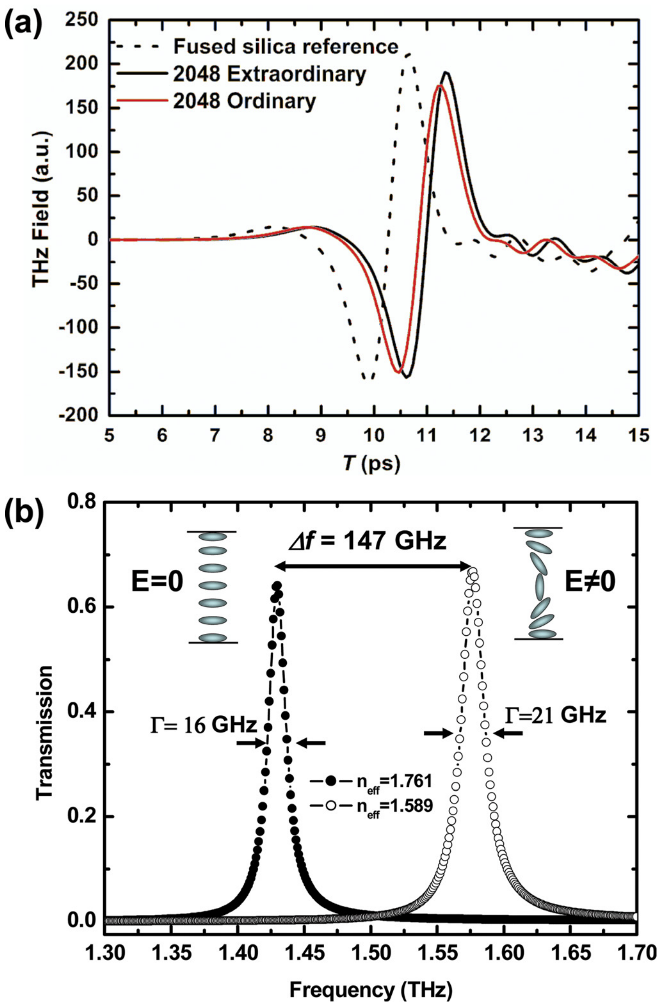

FIG. 3. (Color online) (a) Experimental waveforms of the THz pulse transmitted through the empty and LC cells at different alignment (ordinary vs extraordinary). (b)The calculated transmission characteristics of the filter. The two alignments of the liquid crystal are shown in the insets.

and perpendicular to the long axis of LC molecules, respectively, D is the electrical displacement in the LC layer, and ϕ is the director angle depicted in the inset of Fig. 4. The initial orientation of the LC (i.e., $V_{\text{bias}}=0$) is set parallel to the MPC surface, assuming strong surface alignment. When applying bias voltage, the LC molecules are reoriented from their initial orientations to z axis that is perpendicular to the MPC surface as depicted in the insets of Fig. 3. The derivative of φ can be obtained using Eq. (1) and the Euler–Lagrange equation. The corresponding effective refractive index at a certain depth and a certain electrical displacement is given by

$$n_{eff}(z,D) = n_e n_o/\sqrt{n_e^2 \sin^2 \varphi(z,D) + n_o^2 \cos^2 \varphi(z,D)}. \quad (2)$$

Then, the averaged effective refractive index, $\bar{n}_{eff}$, of the whole LC layer can be calculated using

$$\bar{n}_{eff}(D) = \frac{2}{d}\int_0^{d/2} n_{eff}(z,D)dz. \quad (3)$$

The electrical displacement D can be replaced by voltage V_{bias} using the relation $D = CV/A$, where A is the area of an

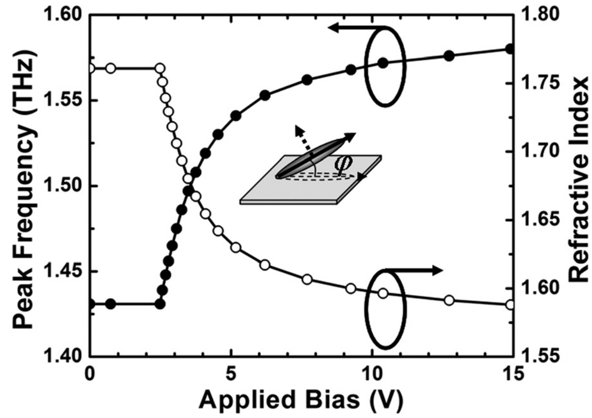

FIG. 4. The peak position (solid circle) of the filter and the refractive index (open circle) of the LC as a function of the applied bias. The director angle of the LC is shown schematically in the inset.

electrode and C is the voltage-dependent capacitance of the LC layer that is given by

$$C(V) = 2\int_0^{d/2} \sqrt{\frac{\varepsilon_1^2 \varepsilon_2^2}{\varepsilon_1^2 \cos^2 \varphi + \varepsilon_2^2 \sin^2 \varphi}} dz. \quad (4)$$

Based on the theories discussed in the preceding text, we calculate the effective refractive index of realistic LC, MLC-2048 (Merck). In the calculations, the experimentally measured optical parameters of the LC are used. The optical parameters are measured using the terahertz time-domain spectroscopy and temporal waveforms of the THz pulses are shown in Fig. 3(a). The corresponding parameters are $n_e = 1.761$, $n_o = 1.570$, $\varepsilon_1 = 11.2$, $\varepsilon_2 = 8$, $K_{11} = 17.7$ pN, and $K_{33} = 21.4$ pN. The effective refractive index as a function of the applied bias is in the range of $\bar{n}_{eff} = 1.589 \sim 1.761$ as shown in Fig. 4.

To see the transmission characteristic of the filter design, a set of the transmission spectra (Fig. 3) is calculated using the maximum effective refractive index ($n_{eff} = 1.761$, $k = 0.01$) and the minimum effective refractive index ($n_{eff} = 1.589$, $k = 0.01$). For these calculation, we employ the imaginary part of the refractive index, $k = 0.01$, which is also measured experimentally, to take into account loss by the LC. The resulting transmissions show some loss due to the interactions with the liquid crystal during multiple reflections between the top and the bottom MPCs. From the calculated transmission spectra, the maximum tunable range of the proposed filter would be $\Delta f = 147$ GHz and the full width at half maximum (Γ) of the transmission peaks is $\sim$16 GHz at $f = 1.430$ THz and $\sim$21 GHz at $f = 1.577$ THz. Comparing with previously proposed designs,[3–5] our design is expected to have wider tunable range. In Fig. 4, the effective refractive index (open circles) and the corresponding peak positions of transmission (solid circles) calculated as a function of applied bias are plotted. The positions of transmission peaks can be finely tuned in the range of $f = 1.430 \sim 1.577$ THz with the operating bias voltage range of $2 \sim 15$ V. The tuning sensitivity is 11.3 GHz/V and the Q-factors are $\sim$89 at $f = 1.430$ THz and $\sim$75 at $f = 1.577$ THz. The fractional tuning range, defined as $\Delta f/f_0$ with Δf = full width of the tuning range and f_0 = central tuning frequency, is $\sim$9.8%.

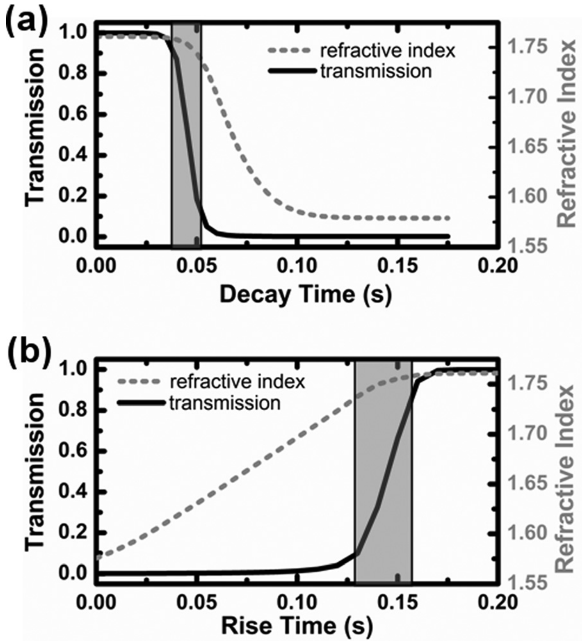

FIG. 5. Time dependent refractive index (dashed line) and normalized transmission (solid line) by frequency modulation. (a) Decay response with frequency changed from 1 to 100 kHz and (b) rise response with frequency changed from 100 to 1 kHz.

IV. SWITCHING PROPERTIES OF THE THz FILTERS

MLC-2048, the LC used in the filter design, is a dual-frequency LC material; this means that the refractive index of the LC can be controlled not only by changing bias voltage (voltage-modulation) but also by changing the frequency of a fixed bias voltage (frequency-modulation).[20] The frequency-modulation can provide shorter fall time than the voltage-modulation, and it also provides reasonably short rise time.[21] A short response time of a LC is critical when a LC embedded optical switch is designed. Combining these with our filter design, a THz switch can be realized. To find time-dependent refractive index change, the dynamic behavior $\varphi(z,t)$ of the LC with a certain voltage V_a is solved using the torque balance equation given by

$$\frac{\partial g}{\partial \varphi} - \frac{d}{dz}\frac{\partial g}{\partial \dot{\varphi}} = -\gamma \frac{\partial \varphi}{\partial t}, \tag{5}$$

where $\gamma = 0.3$ Pa is the rotational viscosity of the LC. Then $\bar{n}_{eff}(t)$ is solved using the same procedures used to find $\bar{n}_{eff}(D)$. The frequency is alternating from 1 to 100 kHz, and the operating voltage is $V_a = 50$ V. The calculated time dependent refractive index (dashed line) and the corresponding normalized transmission ($Tr/Tr_{at\ peak}$) at a fixed frequency $f = 1.430$ THz (solid line) are plotted in Fig. 5. The response time is defined as the time interval for the change of transmission from 10% to 90% or vise versa. In Fig. 5(a), the frequency is modulated from 1 to 100 kHz, and the resulting response time (decay time) is ~12.5 ms. In Fig. 5(b), the frequency is modulated from 100 to 1 kHz, and the resulting response time (rise time) is ~25 ms. One interesting feature in the results is that the response of transmission is faster than that of the refractive index. This is because the transmission spectra are very narrow as shown in Fig. 3, and thus the resulting transmission rapidly changes with a small variation of the refractive index. The response times are similar to the previously reported experimental results.[21] Although there is a limitation of switching time imposed by the response time of the liquid crystal, the intrinsic ability of a defect mode to tune optical response not only by changing the refractive index but also by changing volume would give more freedom to select faster responding electro-optic materials.

V. CONCLUSIONS

In conclusion, an LC embedded MPC THz tunable filter is designed, and the filter properties and the switching properties of it are investigated. The tunable THz filter is based on the voltage-modulation of LC molecules, and the tunable range is calculated to be $f = 1.430{\sim}1.577$ THz with bias voltage of 2~15 V. The switching property of the filter is based on the frequency-modulation of LC molecules and the order of milliseconds switching is observed.

ACKNOWLEDGMENTS

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